RENSSELAER POLYTECHNIC INSTITUTE

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NATIONAL AERONAUTICS AND
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Submitted by

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Summary

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The instrumentation and theoretical development for the study of electromagnetic wave propagation in magnetoplasmas has been completed. Data has been taken on polarization ellipses which have traversed the plasma. The appropriate transformation matrix has been experimentally determined. It has been used successfully to predict the behavior of the magnetoplasma. In order to accomplish this work a plasma has been successfully generated by a pulsed, r.f. generator in a magnetic field, and a phase locked circuit which enables the wave polarization ellipse to be displayed on an oscilloscope has been completed and brought into operating condition. Performance data has been taken on two Fresnel plate lenses designed to operate at 19.3Gc. Electron loss coefficients and electron temperature measurements have been analysed for an afterglow study of nitrogen gas. A mechanism for the recombination process is suggested. A microwave reflection technique has been applied to the study of nitrogen plasmas. A time of flight mass spectrometer for ion analysis in plasmas is under construction. An initial attempt to detect an electron beam-plasma interaction using the Rensselaer Linear Accelerator has been unsuccessful. A study of the harmonic content of the beam is being made.

Papers, Technical Reports and Conference Presentations

1. J. E. Rudzki, E. H. Holt, "A 10 Kilogauss Air Cooled Magnet for Plasma Research," Plasma Research Laboratory, R.P.I., TR no. 6, January, 1963.

2. W. C. Taft, K. C. Stotz, E. H. Holt, "A Gated Radiometer for Plasma Afterglow Study," Plasma Research Laboratory, R.P.I., TR no. 7., April 1963. Paper read at the I.E.E.E. International Convention, New York, March 25-29, 1963 and to be published in the Conference Proceedings.

1. Electromagnetic Wave Propagation in Magnetoplasmas

The theoretical and experimental preparations for this study have been completed. The transformation matrix which describes the interaction of the magnetoplasma medium on the propagating electromagnetic wave has been experimentally determined. It has been used to calculate the effects of the magnetoplasma on electromagnetic waves of various polarizations. The resulting predictions have been checked experimentally. Agreement of theory and experiment within the limits of the experimental accuracy is obtained.

In order to accomplish this work the following problems were solved during the period under review:

A plasma was successfully generated in the presence of a strong magnetic field by a pulsed radio frequency power source; the phase locked circuit which enables the wave polarization ellipse to be displayed on an oscilloscope was completed and brought into operating condition; the microwave polarimeter circuit was calibrated.

This study has been the topic of a Ph.D. thesis by R. E. Haskell. The abstract reads as follows:

"The change in the polarization of an electromagnetic wave resulting from passage through an anisotropic plasma is studied. A systematic technique for handling elliptically polarized waves based on the properties of the Poincare sphere is developed. A method of analyzing polarizations in terms of orthogonal elliptical polarizations is described. An analysis of electromagnetic wave propagation in anisotropic plasmas in terms of the principal axes is carried out. Expressions which tell how a wave of arbitrary polarization will change as it propagates along the magnetic field in an anisotropic plasma are obtained. A new method for determining the transformation matrix of a given plasma from two polarization measurements is described. From these measurements the polarization transforming properties of the plasma are completely specified. In particular, techniques are described which predict the wave polarization which propagates unchanged through the plasma and the wave polarization which propagates with maximum intensity. Polarization experiments involving the free space propagation of microwaves through a laboratory plasma are described. The results show that the method leads to accurate predictions of the behavior of electromagnetic waves in magnetoplasmas."

This work is being prepared for submission as a technical report (no. 8 of the Plasma Research Laboratory). Some of the work done in this area will now be described.

R.f. Breakdown in a Magnetic Field

An attempt was made to form the plasma inductively. The rf pulses were fed to a tank circuit with the energy coupled to the plasma vessel in the manner shown in Figure 1a. At resonance the large rf current flowing through the coil produces a large, axial rf magnetic field which induces an azimuthal electric field in the vessel. This electric field produces

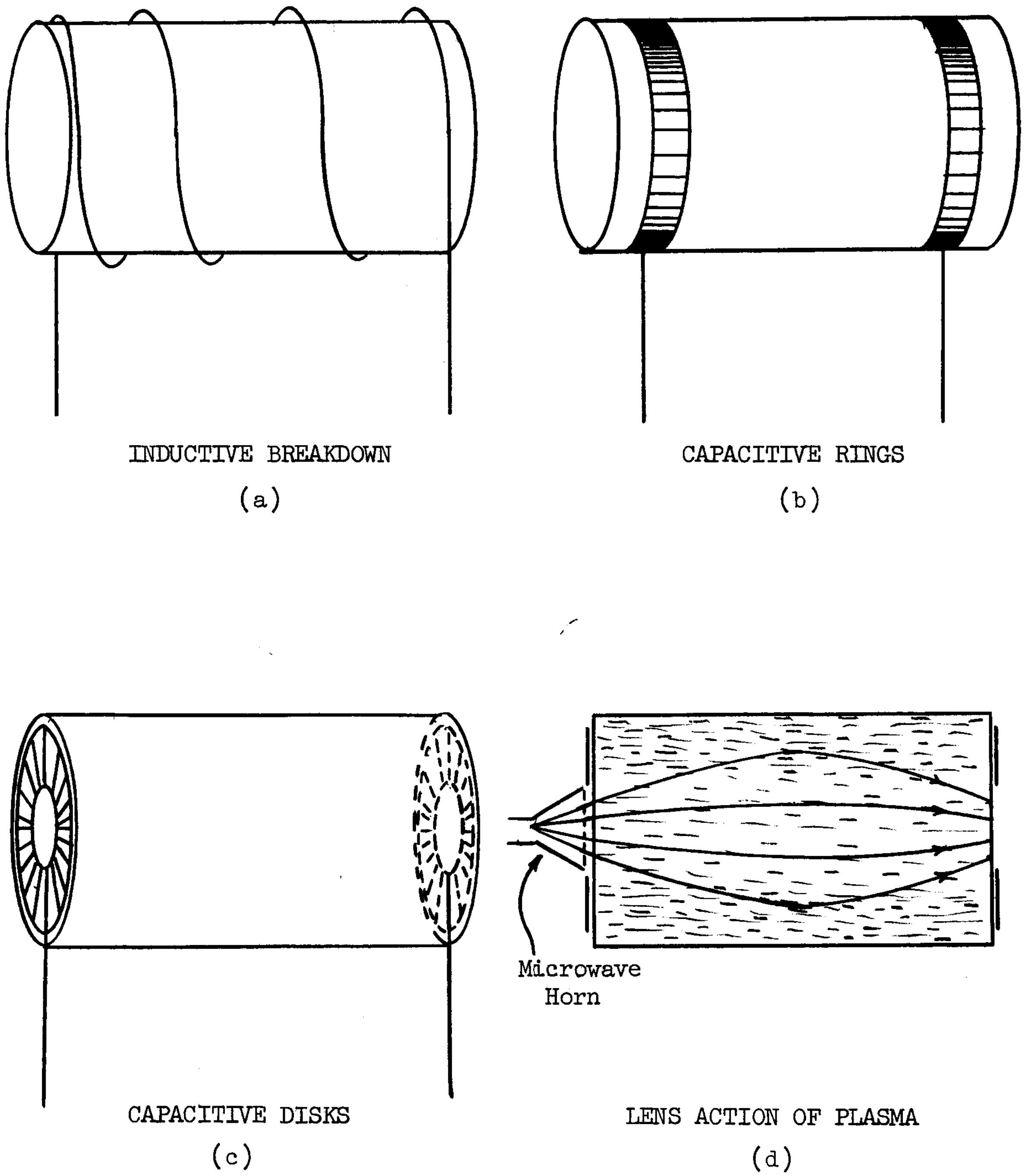

Figure 1. R.f. Plasma Formation - Electrode Configurations.

ionization and breakdown of the gas. In the absence of an external magnetic field a bright plasma was formed. However, when an external magnetic field was applied the plasma was confined almost entirely to the walls of the vessel. The azimuthal electric field is strongest near the walls of the vessel. Ionization therefore takes place most readily near the walls. The effect of the external magnetic field is apparently to prevent those electrons which are formed near the walls from readily moving across the magnetic field lines toward the center of the vessel.

An electrode configuration in which the electric field was more axial would be expected to reduce the effect of the external magnetic field on the ionizing electrons. The tank circuit was therefore modified so that the rf energy was fed to the plasma vessel by capacitive electrodes. The voltage across the capacitor in the tank circuit was 4000 volts peak to peak. The first electrode geometry tried was the capacitive ring configuration shown in Figure 1b. A fairly uniform plasma was formed in the absence of an external magnetic field. However, when the magnetic field was applied the plasma was again confined to the walls of the vessel. The electric field, although axial, is still strongest near the walls of the vessel and those electrons produced there are still prevented from moving easily toward the center of the vessel.

Several other configurations were tried and similar results were obtained. Finally, the capacitive disks shown in

Figure 1c produced satisfactory results. When the external magnetic field was applied the plasma became less dense in the center and was the brightest in the annular region directly between the two disks.

An interesting feature of the polarization measurements is the fact that in many instances the output amplitude has a greater intensity than the input amplitude. A probable explanation of this phenomenon is the focusing action of the dense annular region described above. In the absence of a plasma the signal from the microwave horn spreads out and only a portion of it is received. However, when the plasma is formed in the magnetic field a lens action of the type shown in Figure 1d causes the received signal to be larger than the signal received in the absence of the plasma.

Phase Locked Circuit for Presentation of the Polarization Ellipse

The microwave circuit used in this study is shown in Figure 2. Details of its operation and calibration are given in the technical report.

A block diagram of the receiving system is shown in Figure 3. A standard frequency of 100 kc is used to phase lock a 2 mc oscillator. This 2 mc signal is then used to phase lock a 28 mc oscillator and a 30 mc oscillator.

The signal from the 30 mc oscillator is compared with the difference frequency of the two klystrons. The resulting error signal is applied to the reflector voltage of klystron

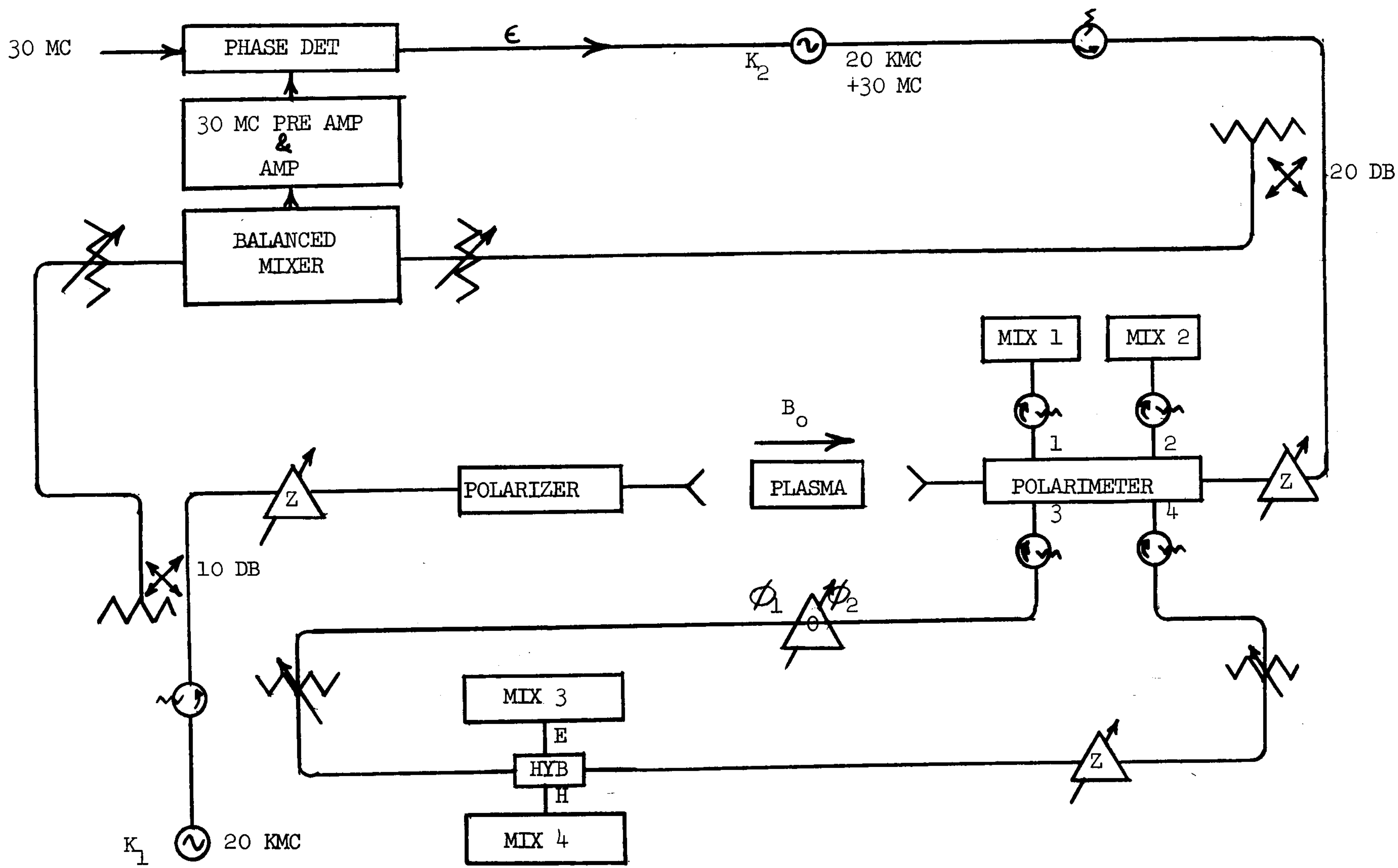

Figure 2. Polarization Studies - Microwave Circuit.

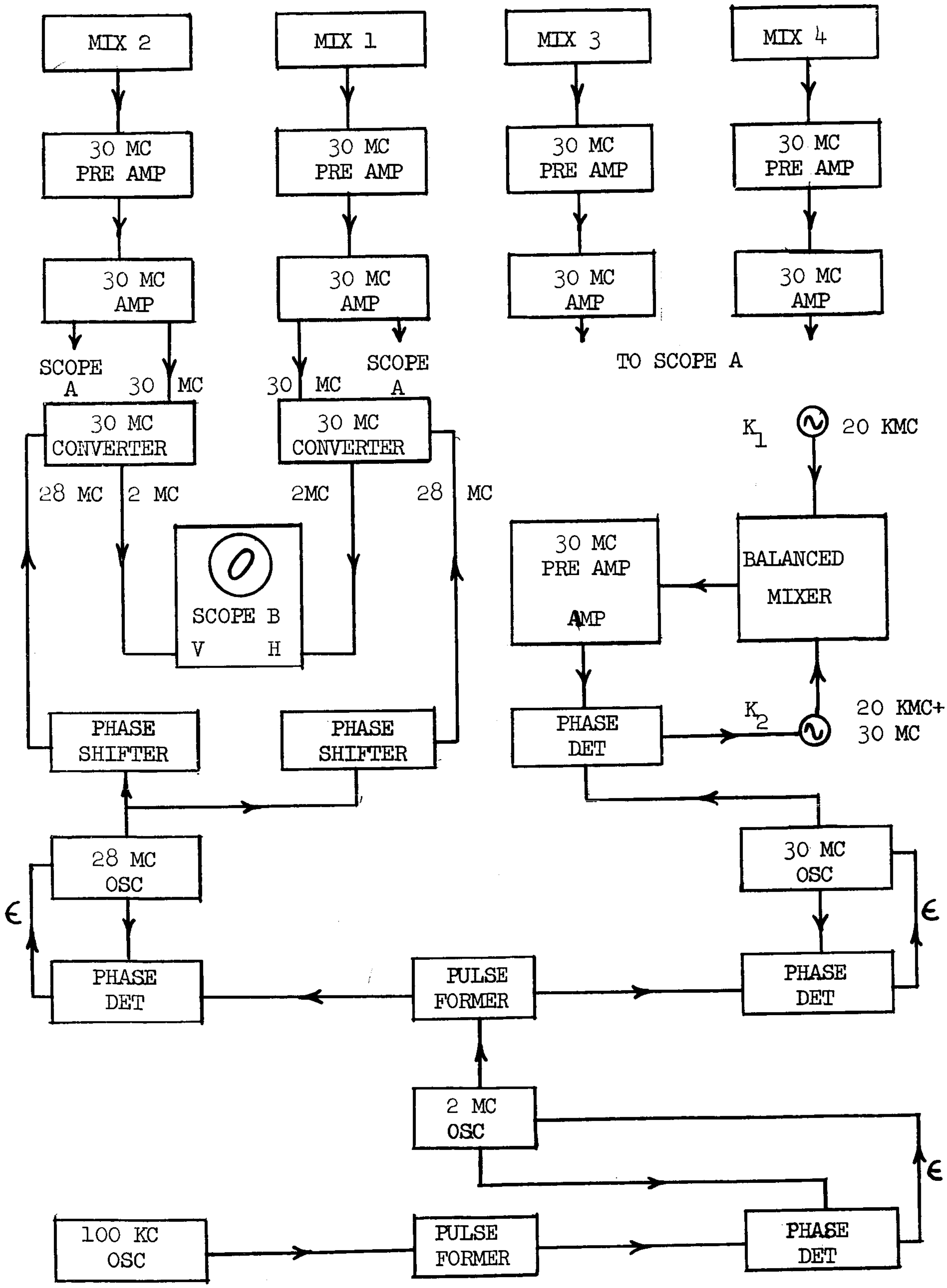

Figure 3. Polarization Studies - Phase Locked Receiving System.

K_2 to keep the frequencies of the two klystrons 30 mc apart.

The 30 mc signals which are produced in Mixers 1, 2, 3, and 4 of the microwave circuit (Figure 2) are each amplified in separate pre-amplifiers and main amplifiers. The detected outputs of each of the main amplifiers are fed to two dual-trace amplifiers in a dual-beam oscilloscope. These signals are used to measure the polarization as a function of time in the plasma afterglow.

Two amplified undetected 30 mc signals from Mixers 1 and 2 are converted to 2 mc signals by mixing each of them with the phase locked 28 mc oscillator. The relative phase of the two 28 mc signals can be varied for calibration purposes by means of separate 28 mc phase shifters. The two 2 mc signals, which are proportional to the vertical and horizontal components of the wave entering the polarimeter, are applied to the vertical and horizontal plates of an x-y oscilloscope. The resulting Lissajous figure is a visual display of the polarization which is being measured.

It is possible to obtain a visual display of the polarization of the wave which emerges from the plasma at any particular time in the afterglow by using the timing sequence shown in Figure 4. Sawtooth waves of negative slope and of 16 msec duration are formed in the Waveform Generator 1. Negative pulses of 600 microsec width are generated at time a by Pulse Generator 1. These pulses have a repetition interval of 16 msec and are used to pulse the 4.7 mc rf generator. The

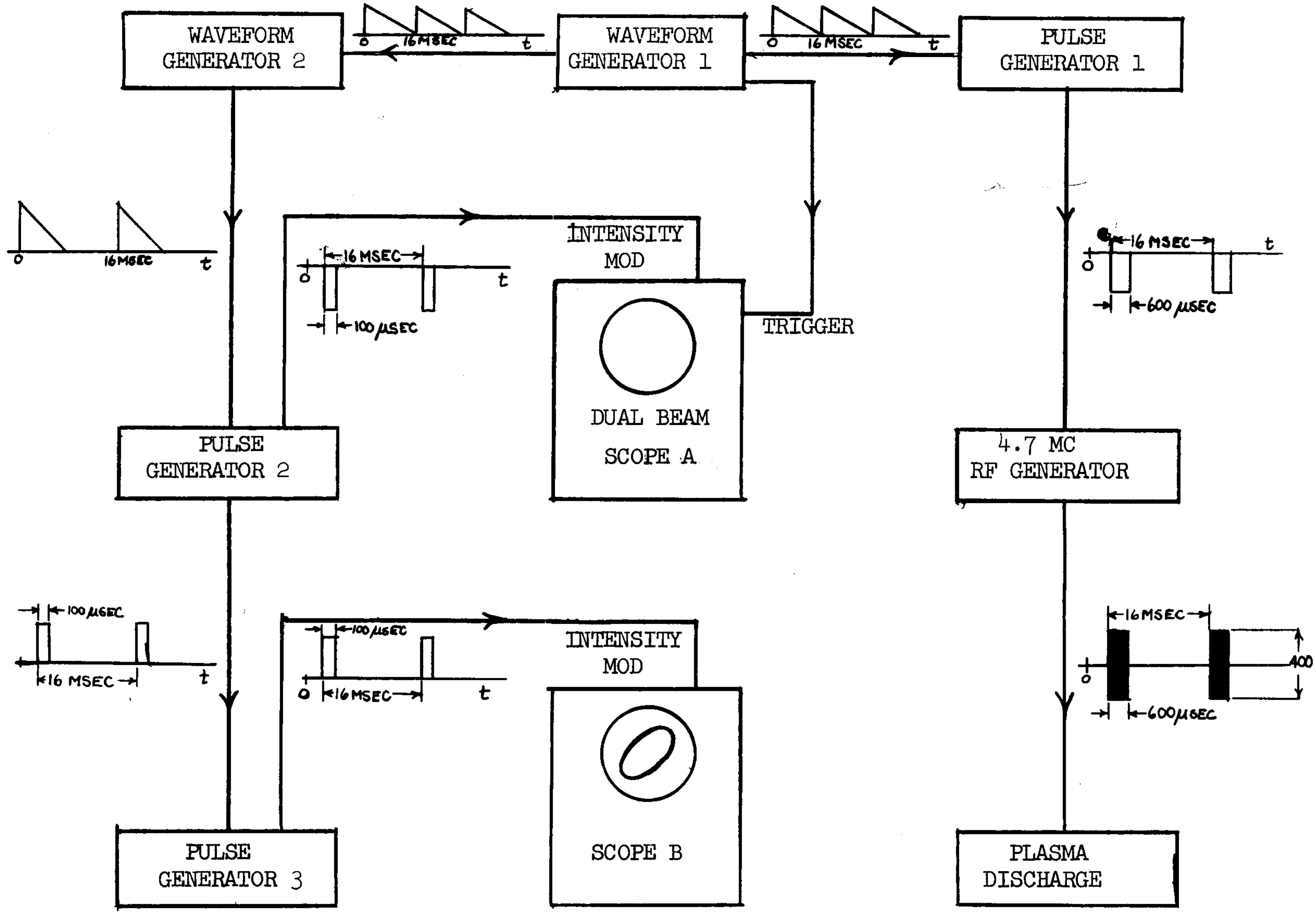

Figure 4. Polarization Studies - Timing Sequence.

plasma discharge is formed during these 600 microsec pulses and then decays in about 4 or 5 msec.

Waveform Generator 2 is triggered from Waveform Generator 1 and produces sawtooth waves of negative slope whose duration can be adjusted to cover the times during which the plasma is decaying. Negative pulses of 100 microsec width are produced at time b (which is greater than time a) by Pulse Generator 2 and are used to intensity modulate the upper beam of Scope A. As a result a bright dot appears at some time in the afterglow trace of Scope A. The dot can be made to appear at any time in the afterglow by varying the delay time b.

A gate from Pulse Generator 2 is used to trigger Pulse Generator 3 which produces positive pulses similar to those of Pulse Generator 2. These pulses are used to intensity modulate Scope B. Thus, at the instant of time in the afterglow indicated by the dot on Scope A, an ellipse appears on Scope B which is a visual display of the polarization of the wave emerging from the plasma at that particular time in the afterglow.

Since the plasma is only produced at 16 msec intervals, another ellipse (of normal intensity) is also displayed on Scope B. This ellipse represents the polarization of the microwave signal in the absence of a plasma. Thus, using this technique, Scope B displays simultaneously the polarization of the wave which enters the plasma and the polarization of the wave which emerges from a given anisotropic plasma.

Fresnel Plates for Production of Beams of Electromagnetic Waves

Two 22 inch diameter Fresnel plates for operation at a frequency of 19.3 Gc have been tested. Both plates have a focal length of 12 inches. A folded zone design was made out of plexiglass. A concentric ring design was made by fixing aluminum foil rings to a plexiglass disc. The beam widths of both plates agreed well with the calculated value of 1.8 degrees. The concentric ring design has a gain which is 8.5db greater than the gain of the folded zone design. The calculated figure was 10db.

This work is the subject of an M.E.E. thesis by R. A. Bitzer. It is being prepared as a technical report (no. 10 of the Plasma Research Laboratory). The abstract is as follows:

"When the electron density of a plasma increases, the frequency of the microwave probing techniques must also be increased. A usual method of probing using microwaves is to fabricate a cell inside a piece of waveguide. This device then forms a part of the microwave circuit. If plasmas of greater density are to be studied, then the feasibility of using this technique becomes less because the size of the waveguide becomes very small.

This paper discusses the possibility of using a lens system for probing the plasma. Such a system would allow a good sized cell to be used and the assumption that a plane wave is propagated through the plasma. The latter assumption would simplify the calculations of electromagnetic wave interaction with the plasma.

Based on the requirements dictated by our experimental apparatus to measure Faraday rotation of an electromagnetic wave in a plasma, certain types of lenses were chosen. The lenses chosen are the dielectric lens and the Fresnel half-period zone plate. Tests were conducted on these lenses and the results are stated. Using these results, a lens system can be used on K band (20 Gc.), but better use of the system can be made in the millimeter wavelength region."

2. Afterglow Study in Nitrogen

This work is the subject of a Ph.D. thesis by K. C. Stotz. The abstract is as follows:

"The nitrogen afterglow has been studied using the microwave transmission technique as a basic diagnostic tool. A concerted effort has been made to simplify the experimental conditions in order to remove some of the questionable assumptions made in previous transmission method experiments. A plasma cell has been developed which consists essentially of a length of standard waveguide, so that a simple rectangular shape with well-defined boundaries is obtained for the microwave-plasma interaction. A microwave bridge circuit is used so that simultaneous measurements of the attenuation and phase shift of the microwave signal passing through the plasma are obtained. A gated microwave radiometer was developed and used to measure the electron temperature variation in the afterglow. A spectroscopic study of the afterglow was made and a method for studying the light intensity as a function of time is discussed. By this variety of techniques, previous results obtained by using the microwave transmission method alone are shown to be in error, and results of the present experiment are shown to be in agreement with microwave cavity measurements. The ambipolar diffusion coefficient times pressure obtained for nitrogen is, $D_a p$ 123 _ 24 cm^2 Torr sec^{-1} in the pressure range 0.2 to 4.5 Torr at room temperature. This corresponds to a mobility at 0^oC, 760 Torr of 2.85 cm^2 sec^{-1} $volt^{-1}$. The recombination coefficient increases with pressure from 4×10^{-8} cm^3 sec^{-1} at 0.25 Torr to 6.8×10^{-7} cm^3 sec^{-1} at 7.1 Torr. The recombination mechanism is attributed to the dissociative recombination of the N_4 ion, although the three-body recomgination of the N_2 ion may play a significant role. The temperature measurements have indicated a source of energy in the early afterglow which has been attributed to the presence of metastable molecules."

This work is being prepared for submission as a technical report (no. 9 of the Plasma Research Laboratory).

Microwave Reflection Method for the Study of Dense Plasmas

Since low level microwave transmission methods are not generally useful in obtaining information about dense plasmas a method for obtaining information is under investigation whereby the reflected signal from the plasma is analyzed.

The X-Band Plasma Cell described in Status Report no. 3 is used. The microwave circuit is shown in Figure 5.

Outputs A and B are detected by crystal detectors and displayed on a dual trace oscilloscope. The traces give a time display of outputs A and B from the time the cell is pulsed until late in the afterglow. Since the reflection coefficient is a function of the ratio of A/B we can find the reflection coefficient as a function of time.

Assuming a uniform distribution of the plasma density in the cell, parallel boundaries and only considering the first reflection from surface (2) at surface (1) (Figure 6), it can be shown that, for the TE_{01} mode,

$$\frac{E_{ref}}{E_{in}} = \rho = \frac{j\omega\mu_o + Z_o\gamma}{j\omega\mu_o - Z_o\gamma}\left[\frac{(j\omega\mu_o)^2 + 2j\omega\mu_o Z_o\gamma e^{-\gamma d} + (Z_o\gamma)^2}{(j\omega\mu_o)^2 + (Z_o\gamma)^2}\right]$$

where $Z_o = Z_o\Big|_{\text{Air } TE_{01}} = \dfrac{j\omega\mu_o}{\sqrt{(\pi/a)^2 - \mu_o\varepsilon_o\omega^2}}$

$$\gamma = \sqrt{\left(\frac{\pi}{a}\right)^2 - \mu_o\varepsilon_p\omega^2 + j\sigma_p\omega\mu_o}$$

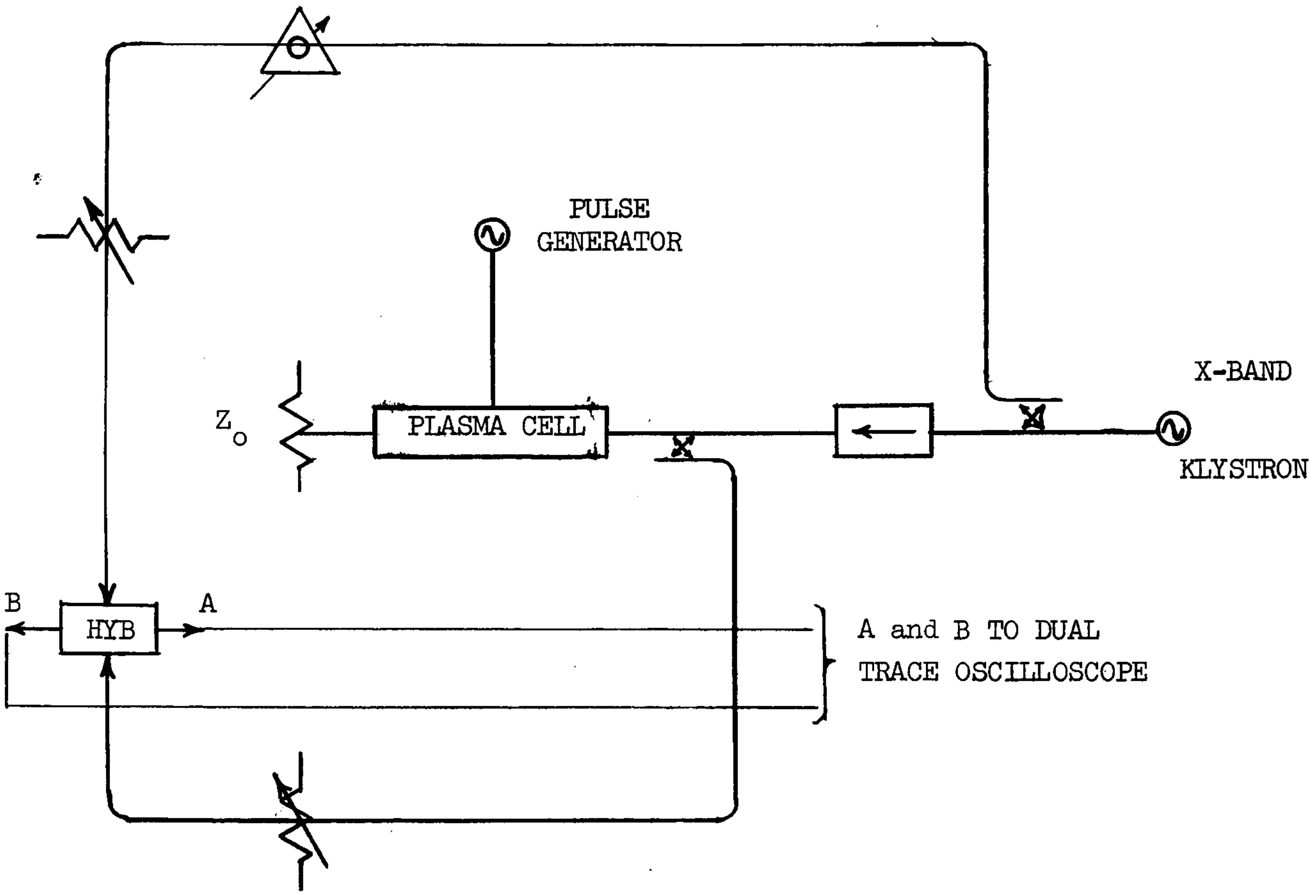

Figure 5. Reflection Measurements - Microwave Circuit.

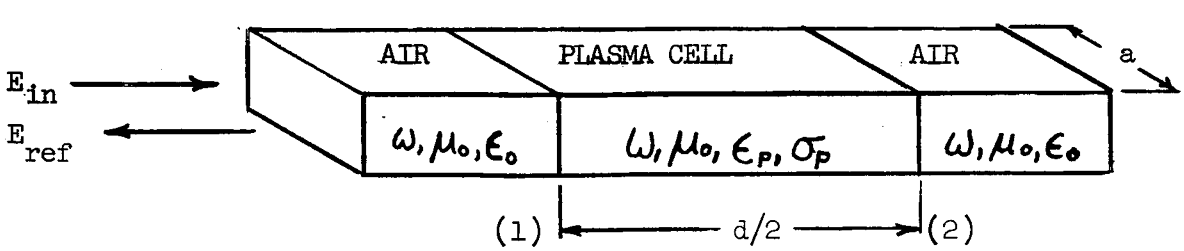

Figure 6. Reflection Measurements - Plasma Geometry.

The subscript zero denotes values for free space.

$\omega/2\pi$ = operating frequency

$$\sigma_p = \sigma_{rp} + j\sigma_{ip} = \frac{n_e q^2}{m(\nu_m + j\omega)}$$

This permits evaluation of the collision frequency ν_m and electron density n_e.

A somewhat similar method for investigation of uniform dense plasmas by microwave reflection has been reported by; T. Tsukishima and S. Takeda in The Journal of Applied Physics, Vol. 33, No. 11, 3290-3291 of November 1962 in a paper entitled "Microwave Reflection By Uniform Dense Plasmas." The authors used a cell similar to that used here but the microwave circuit used standing wave indicators for calculating the reflection coefficient. The authors reported measuring electron densities from 2×10^{13} cm^{-3} to 3×10^{11} cm^{-3} in argon gas at a pressure of 0.5 torr.

In our work data has been taken in nitrogen gas in the pressure range 0.5 - 1.2 torr. It is presently being evaluated.

Time of Flight Mass Spectrometer for Afterglow Analysis

An instrument specially suited to the analysis of plasma afterglows has been designed and is under construction. The drift tube is shown in Figure 7. A block diagram of the complete system is shown in Figure 8.

This work is the subject of a B.E.E. thesis by J. J. Sirota entitled, "Design of a Time of Flight Mass Spectrometer."

3. Electron Beam-Plasma Interaction

An initial attempt to detect electromagnetic waves outside a plasma vessel, when bunches of relativistic electrons were traversing the plasma, was unsuccessful. A study is being made of the harmonic content of the Linear Accelerator beam which was used.

4. Disbursement of Funds

A separate report is submitted by the Comptroller's office.

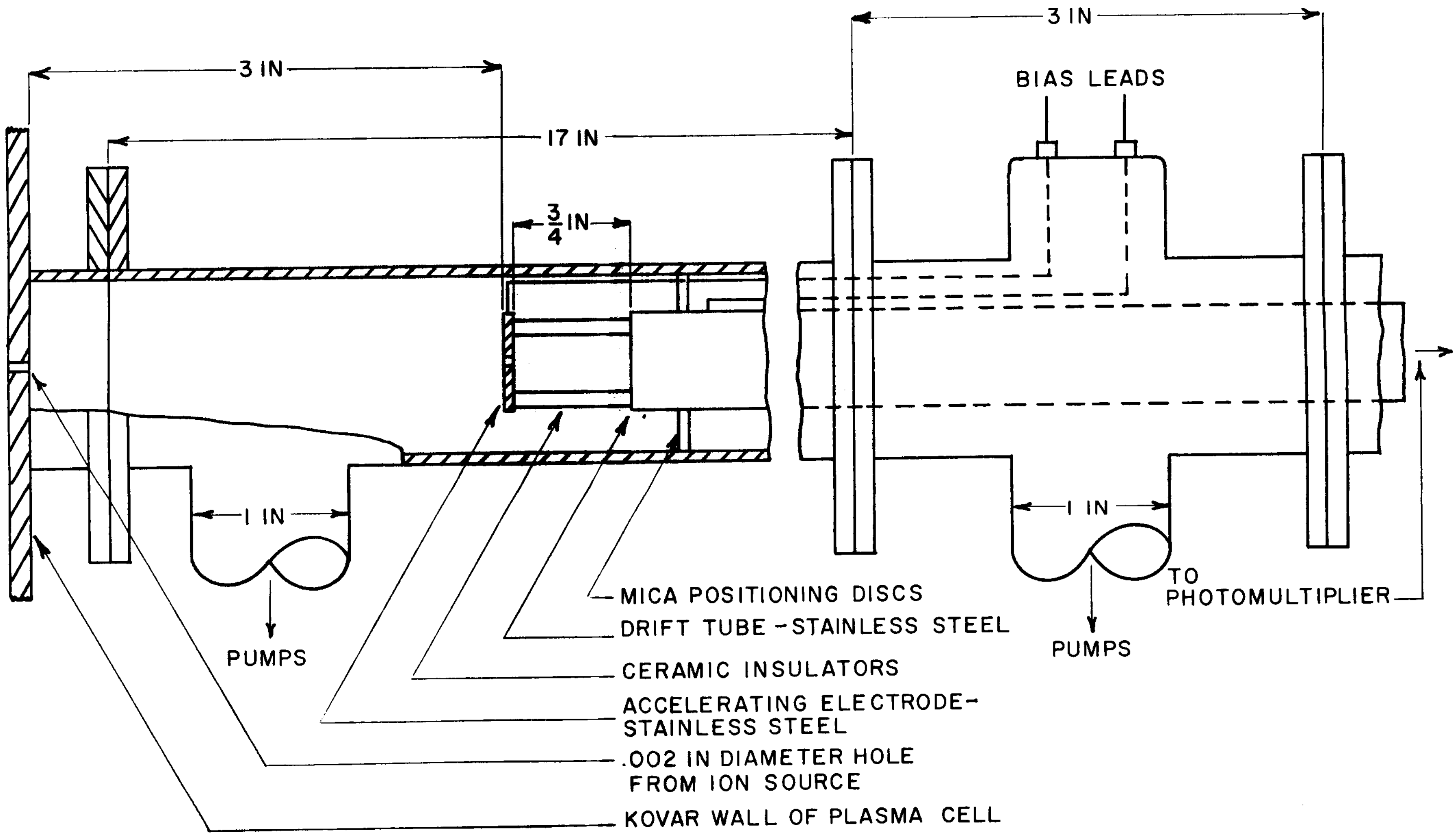

Figure 7. **Time of Flight Mass Spectrometer - Drift Tube**

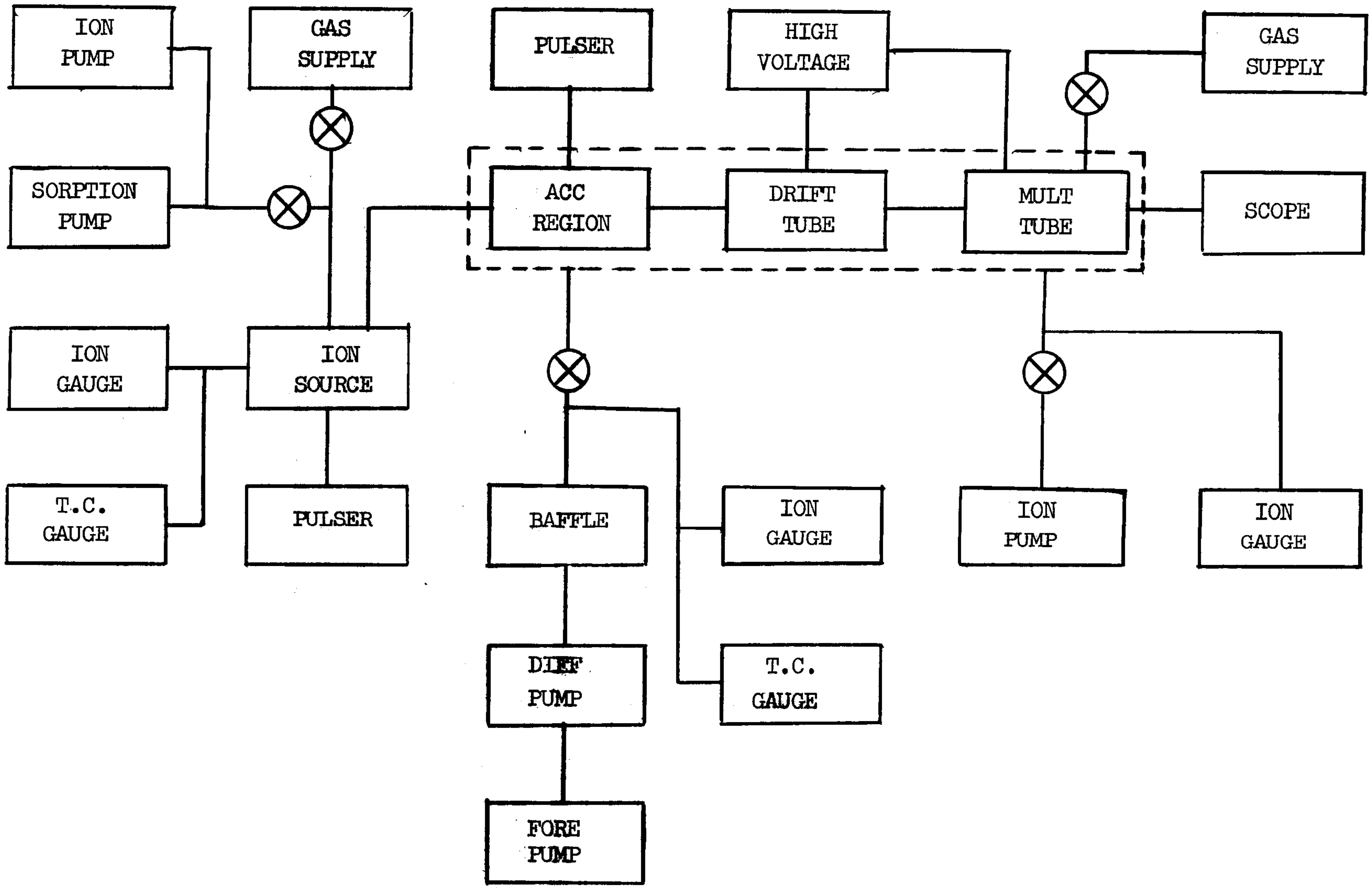

Figure 8. Time of Flight Mass Spectrometer - Block Diagram.

5. Personnel

	Name	Position	Percent Time	
	Professional Personnel			
1.	E. H. Holt	Associate Professor Senior Investigator	50	
2.	K. C. Stotz	Assistant Professor	(50)	
3.	W. C. Taft	Instructor	25	
4.	R. E. Browne	Research Assistant	100	
5.	J. Mendell	Graduate Assistant	50	
6.	R. E. Haskell	Graduate Student	(100)	
7.	R. A. Bitzer	Graduate Assistant	25	terminated Jan.25,1963
8.	D. A. Huchital	Graduate Student	(20)	
9.	W. C. Schwartz	Graduate Student	(20)	
10.	J. J. Sirota*	Undergraduate Student	(20)	

Figures in brackets indicate participation without charge to the grant.

*National Science Foundation Undergraduate Research Participant

Support Personnel

Name	Position	Percent Time
H. Struss	Research Assistant (model shop)	50
J. Wright	Electronic Technician	50
Mrs. M. Santerre	Typist	75
R. Quinn	Student Technician	25

6. Program for the Period May 1 - October 31, 1963

A comprehensive series of measurements of electromagnetic wave polarizations in finite anisotropic plasmas will be made.

Work will continue on the afterglow studies with attention paid to the effect of input pulse energy, measurements of reflection coefficients and studies of electron gas temperature relaxation.

Analysis of the harmonic content of the linear accelerator beam will be made with a view to establishing valid conditions for further measurements of beam-plasma interactions.